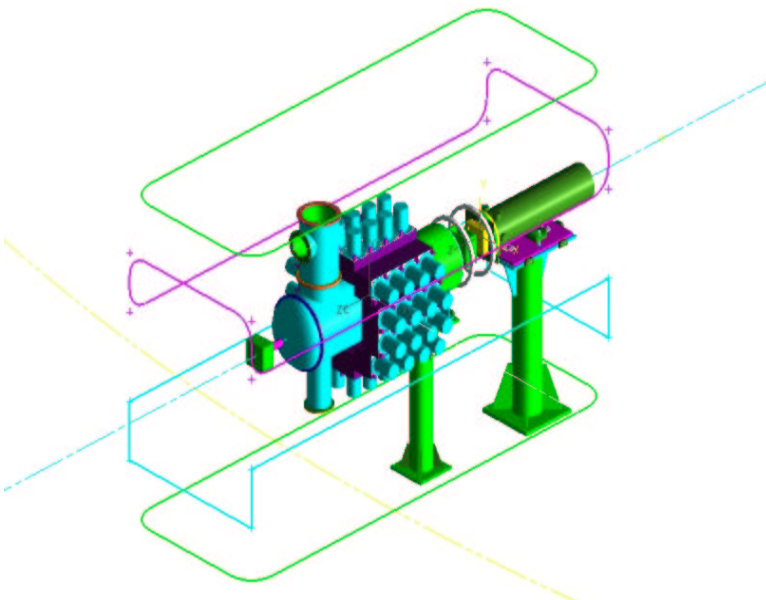
A measurement of the parity-violating gamma-ray asymmetry in the radiative *n*-*p* capture



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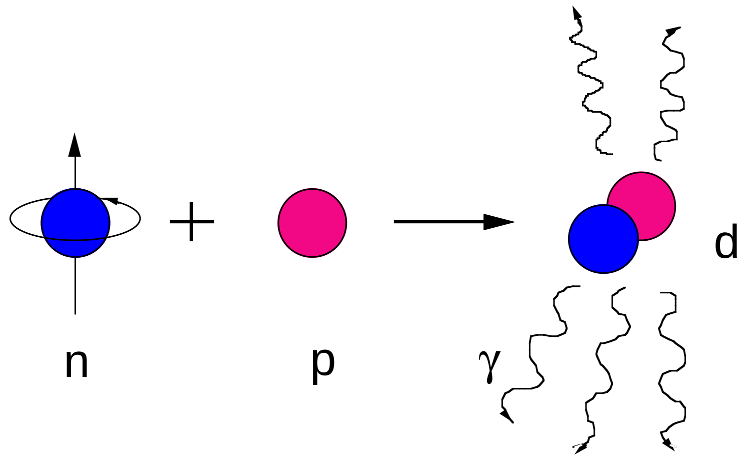
The NPDGamma studies weak interaction between neutrons and protons in the $\dot{\mathrm{n}} + \mathrm{p} \rightarrow \mathrm{d} + \gamma$ (2.2 MeV) reaction. The experiment will measure A_γ, the parity-violating asymmetry in the distribution of emitted γ's



$PV \rightarrow$ signature of the weak interaction, in the strong interaction parity is conserved.

Expected asymmetry $A_\gamma \approx -5 \times 10^{-8}$

Goal experimental error $\leq 0.5 \times 10^{-8}$

A_γ is a clean measurement of H_π^1 since

2-body system - no nuclear structure uncertainties

$$A_\gamma \approx -0.045 \quad H_\pi^1$$

Weak Interaction

- Standard model specifies well how point like leptons and quarks interacting weakly by exchanging a weak boson; W^+, W^-, Z^0, ...
- We do not have a good picture of the weak interaction between hadrons.
- The strong interaction binds nucleons together to form nuclei, and is thus the primary interaction between protons and neutrons. Nucleon interactions take place on a scale of $1/m_\pi \approx 1.5$ fm, short range repulsion.
- The masses of the weak bosons are large and therefore their Compton wavelengths are in range of $1/M_\mathrm{W} \approx 10^{-3}$ fm which is very small compared to the distances characterizing low-energy N-N interactions.

At low energies weak interaction between nucleons cannot be explained by a simple Z or W - exchange. The picture is complicated by strong interaction.

The ratio of weak and strong amplitudes is $4\pi G_\mathrm{F} m_\pi^2 / g_{\pi NN}^2 \approx 10^{-7}$

Low-Energy Hadronic Weak Interaction: ΔI=1 neutral current component

- At low energies hadronic weak interaction can be considered as a point interaction of two currents; the charged and neutral weak currents

$$H_{\mathrm{W}} = \frac{G_{\mathrm{F}}}{\sqrt{2}}(J_W^+ J_W + J_Z^+ J_Z) = H_{\mathrm{L}} + H_{\mathrm{SL}} + H_{\mathrm{NL}}(\Delta S = 1) + H_{\mathrm{NL}}(\Delta S = 0)$$

- From isospin structure of the weak interaction for strangeness conserving ΔS = 0 part is obtained:
  - Charged current weak *N*-*N* interaction components are ΔI = 0 and 2 but not to ΔI = 1.
  - Neutral currents components are ΔI = 0, 1, 2.

$\Rightarrow$ The neutral current should dominate the isospin ΔI = 1 channel.

$\Rightarrow A_\gamma$ in $\dot{n} + p \rightarrow d + \gamma$ is a measure of the ΔS = 0, ΔI = 1 part of the hadronic weak interaction and thus neutral current part of the interaction.

The main goals of the experiments are:

- to isolate the neutral current and
- to understand the mechanism by which the weak force is communicated over the long distances of *N*-*N* interactions.

The Low-Energy *N*-*N* Weak Interaction: one-meson exchange model

The low-energy *N*-*N* weak interaction is conventionally described in a one - meson - exchange model, where one meson - nucleon vertex is weak and the other strong. This long - distance mechanism dominates at nuclear densities.

The six weak *PV* couplings;

$$H_\pi^1, H_\rho^0, H_\rho^1, H_\rho^{1'}, H_\rho^2, H_\omega^0, H_\omega^1$$

characterize the strengths of

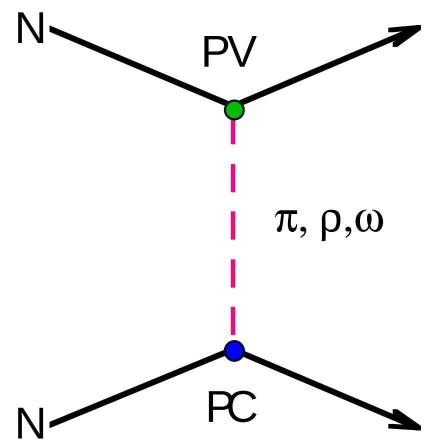
isovector π

isoscalar/isovector/isotensor ρ

isoscalar/isovector ω

weak meson-nucleon couplings.

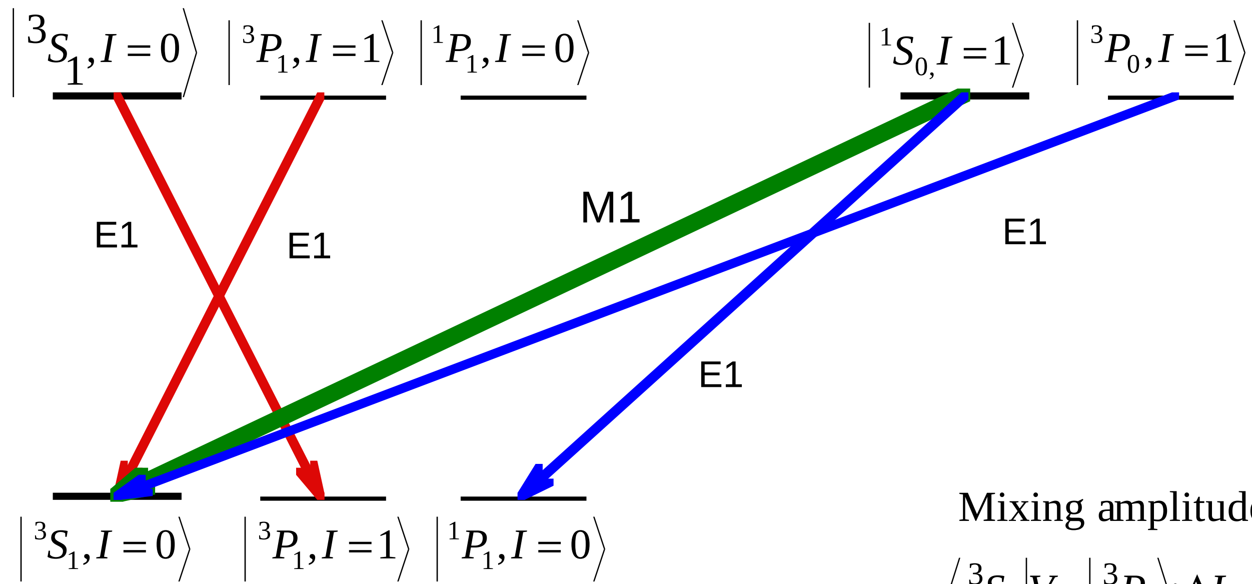
Measured in various combinations by a variety of observables.



$A_\gamma \approx -0.045 H_\pi^1$. The $\pi^\pm$ carries the important long-range part of the hadronic weak interaction, just as it does for the strong interaction.

Simple Level Diagram of *n*-*p* System; $\dot{n} + p \to d + \gamma$ is primarily sensitive to the ΔI = 1 component of the weak interaction

Low-energy continuum states



Bound states

Mixing amplitudes:

$\left\langle {}^3S_1 \middle| V_W \middle| {}^3P_1 \right\rangle; \Delta I = 1$

$\left\langle {}^3S_1 \middle| V_W \middle| {}^1P_1 \right\rangle; \Delta I = 0$

$\left\langle {}^1S_0 \middle| V_W \middle| {}^3P_0 \right\rangle; \Delta I = 2$

- Weak interaction mixes in *P* waves to the singlet and triplet *S*-waves in initial and final states.
- Parity conserving transition is *M*1.
- Parity violation arises from mixing in *P* states and interference of the *E*1 transitions.
- A_γ is coming from ${}^3S_1$ - ${}^3P_1$ mixing and interference of *E*1-*M*1transitions - ΔI = 1 channel.

Measurement of the Parity - Violating Gamma Asymmetry A_γ in the Capture of Polarized Cold Neutrons by Para-Hydrogen, $\vec{n} + p \rightarrow d + \gamma$

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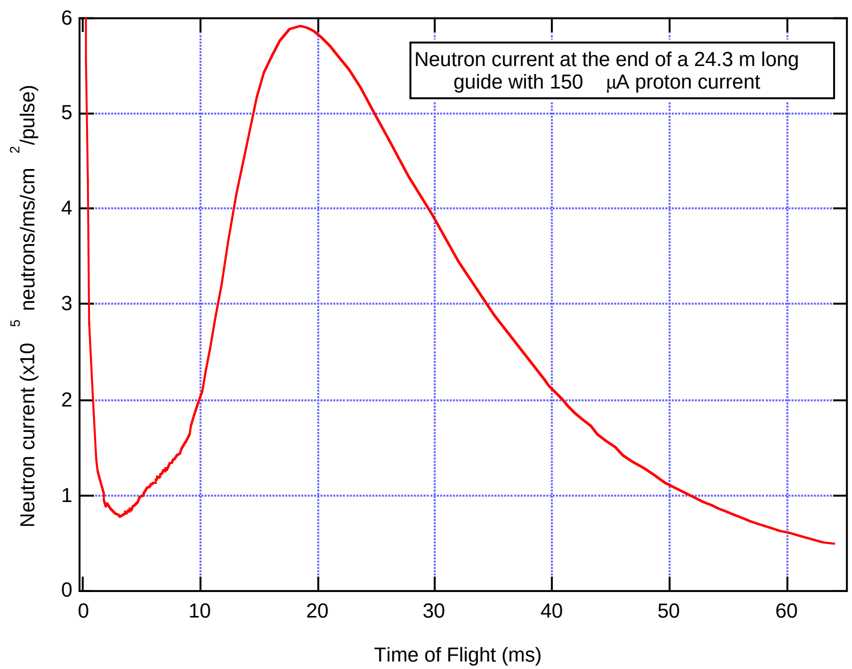
The $\vec{n} + p \rightarrow d + \gamma$ Experiment is Designed for the LANSCE Pulsed Cold Spallation Neutron Source

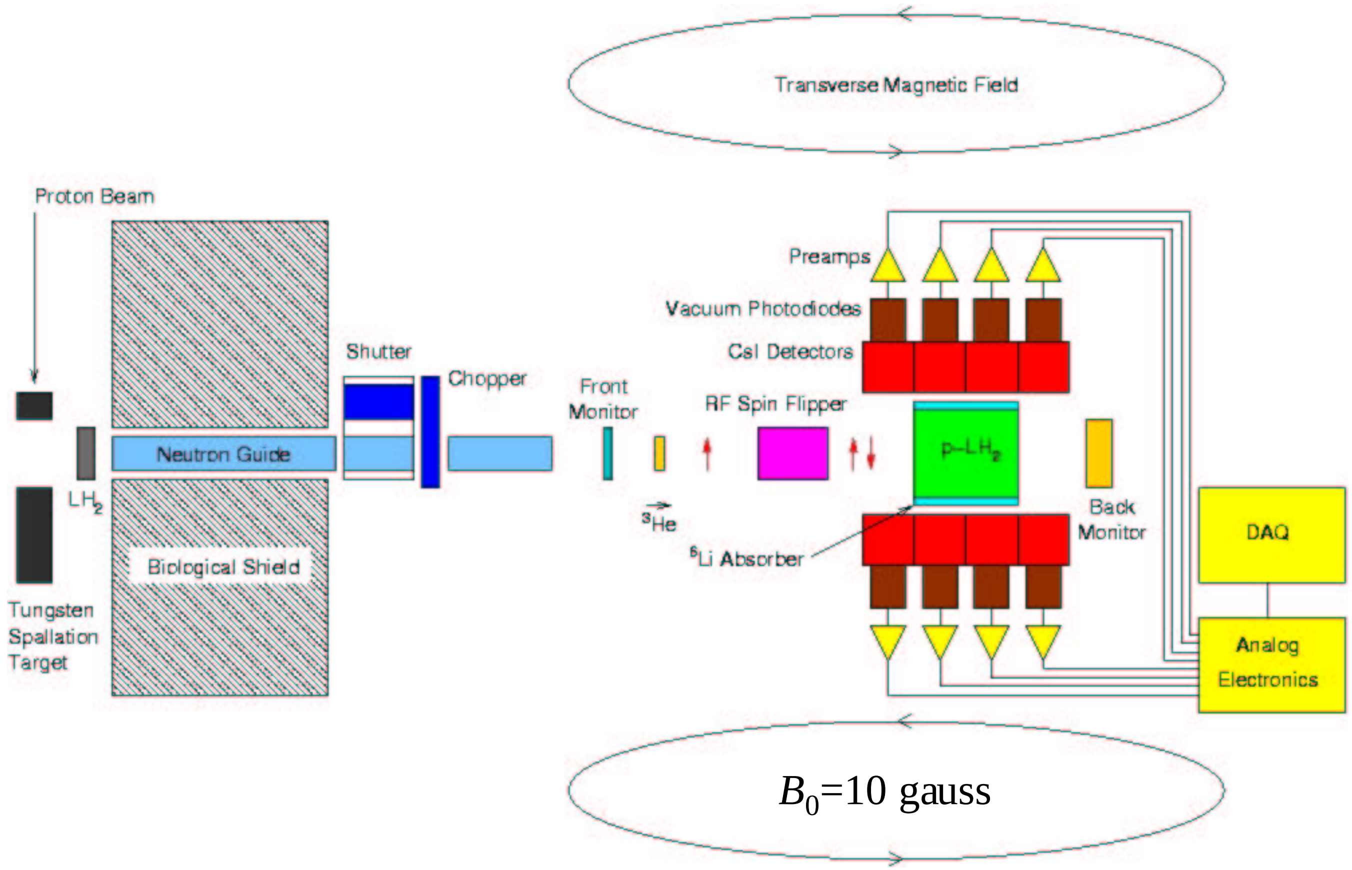
The goal experimental error of 0.5×10^{-8} is a challenge for a polarized cold neutron flux from a spallation source as well as for the control of systematic errors.

- Some 4×10^{17} neutrons are required for statistics.
- Neutron time-of-flight used to design the experiment with systematic errors less than 0.5×10^{-8}.



The flight path 12 at LANSCE has a peak flux of 2×10^{7} n/cm^2/s at about 8 meV.
Neutron pulse rate is 20 Hz $\rightarrow$ *TOF* frame = 50 ms.
To reach the statistics of 0.5×10^{-8} eight months of running is needed.

NPDGamma Experimental Setup



$$\frac{d\omega}{d\Omega} = \frac{1}{4\pi}(1 + A_\gamma \cos(\Theta_{\sigma_n \cdot k_n}))$$

Neutrons Polarized by Optically-Polarized ^{3}He Spin Filter

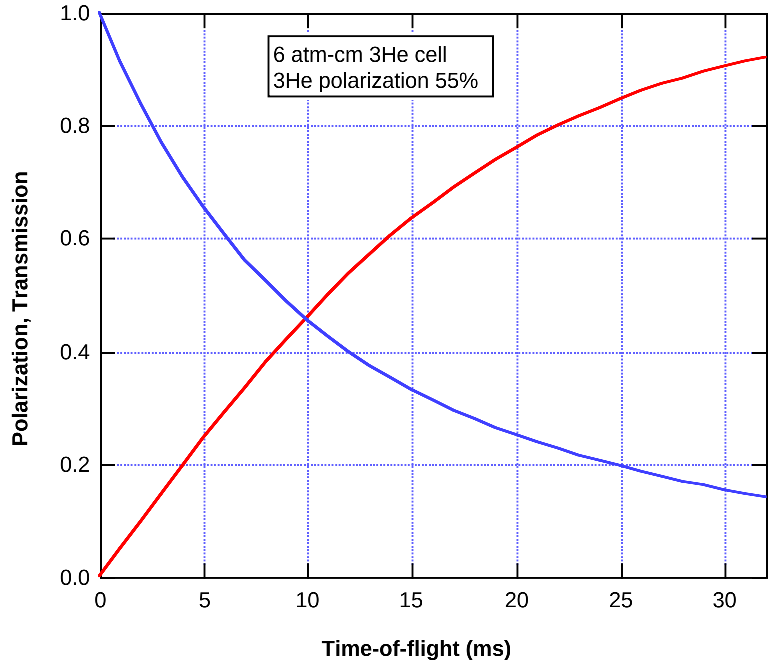
$$P_n = \tanh[nl\sigma_p(E_n)P_{He}]$$

$$T_n = T_n^0 \cosh[nl\sigma_p(E_n)P_{He}]$$

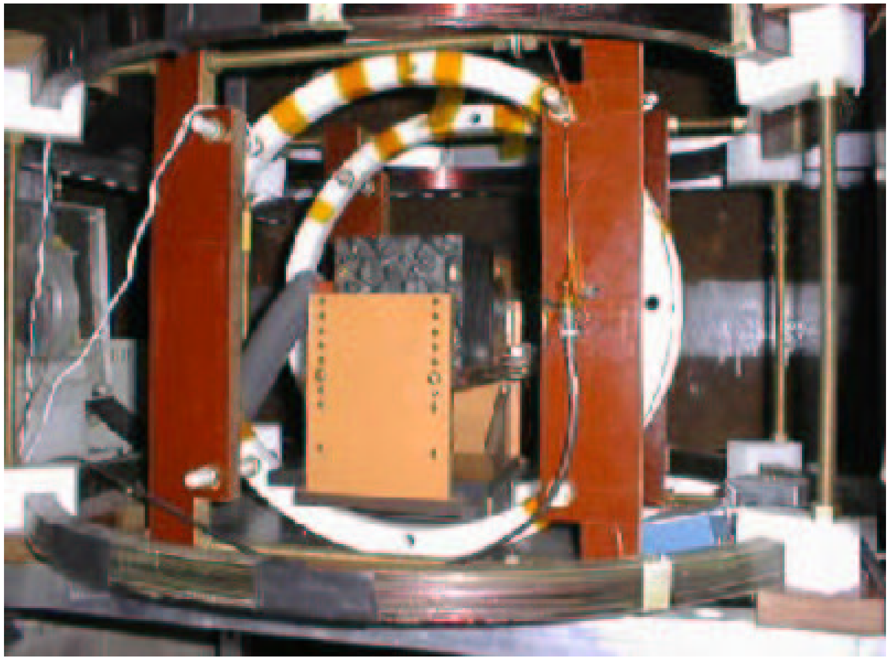
$$P_n = (1-(T^0_n/T^p_n)^2)^{1/2}$$

^{3}He neutron spin filter:

- In a ^{3}He cell Rb atoms are polarized by laser light. Through spin exchange ^{3}He gas is nuclear polarized.
- Cross section of the n-^{3}He singlet state is much larger than the triplet state.
- Therefore, neutrons with spin antiparallel with ^{3}He spins are absorbed and neutrons with spin parallel with ^{3}He spins are transmitted → neutron spin filter



^{3}He Spin-Filter Setup



A 11-cm in diameter cell has T_1> 500 hr. ^{3}He polarization 52% has been measured.

- Large area, 11 cm in dia, ^{3}He cells are required to cover the beam.
- ^{3}He spin filter allows a compact experimental setup.
- ^{3}He spin filter offers an extra spin flip without a change of the *B* field.

100 W light at 795 nm

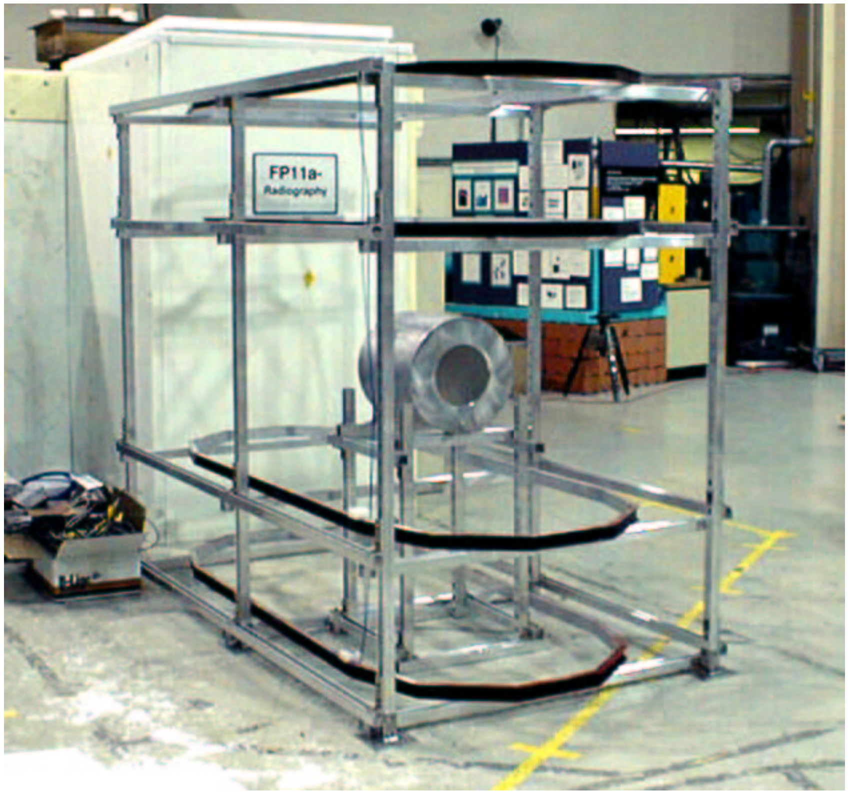
RF Neutron Spin Flipper: spin reversal in broad neutron energy range

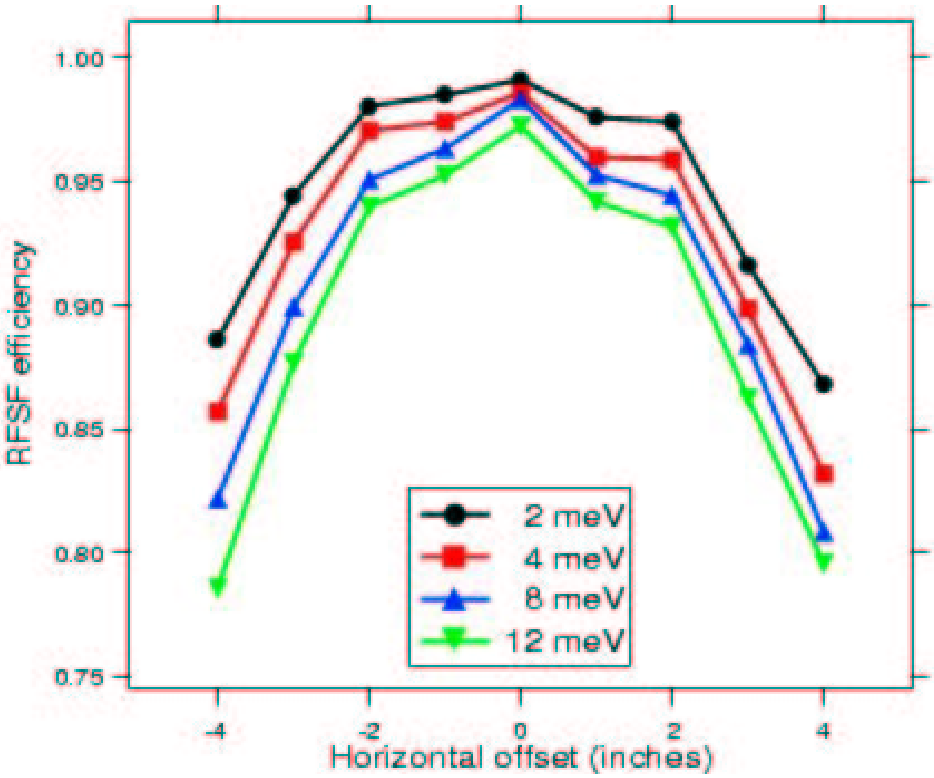
- Neutron spin is guide by a B_0 = 10 gauss field.
- Magnetic gradients has to be < 1 mgauss/cm - no Stern-Gerlach steering $\rightarrow$ false asymmetry
- RF spin flipper (RFSF) is the main control of systematic errors. Spin flip at 20 Hz.
- Magnetic field fluctuations less then 20 mgauss.
- Spin reversal with a RF field.
  - E_n in is proportional to $1/(tof)^2$
  - At resonance a tilt angle of the spin is $\Theta = \gamma B_1 \Delta t$
  - To precess a neutron spin by $\Theta = \pi$

    B_1= (πL_γd_(__*tof)*
  - Spin-flip efficiency > 95% achieved.

Other spin flips are guide field or ^{3}He poalrization

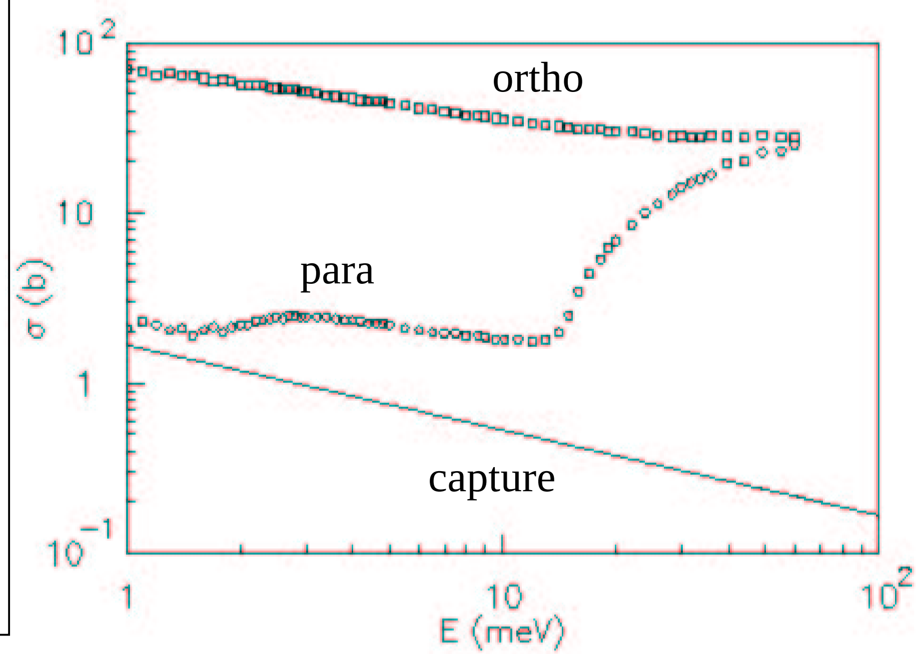
RF Spin Flipper; spin-flip efficiency





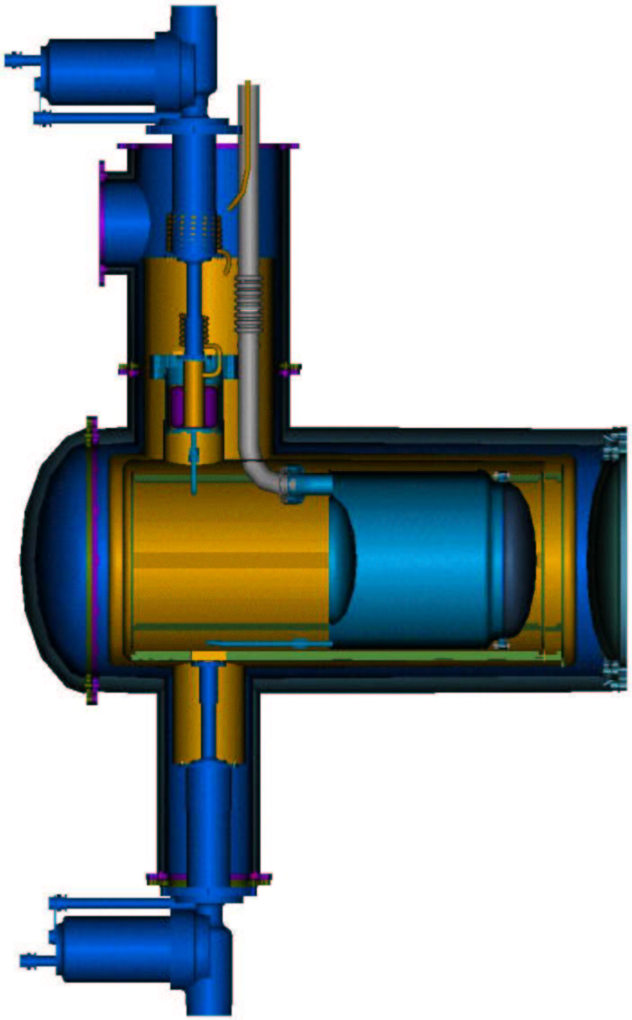
20-liter Liquid Para-Hydrogen Target

- To maintain neutron spin in scattering a para- hydrogen target is required.
- The 30 cm in diameter and 30 cm long target captures 60% of incident neutrons.
- At 17 K only 0.05% of LH_2 is in ortho state $\rightarrow$ 1% of incident neutrons will be depolarized.
- Target cryostat materials selected so that false asymmetries < 10^{-10}.



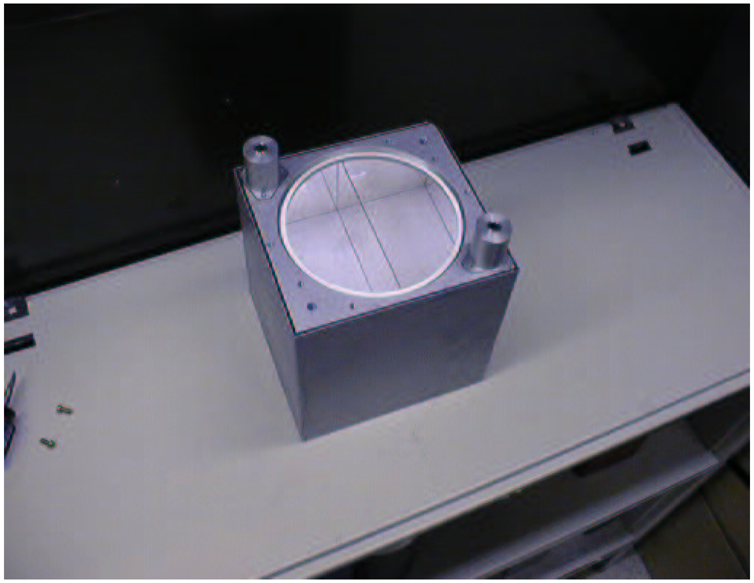
Neutron mean free paths at 4 meV in
- ortho-hydrogen is $\lambda \approx$ 2 cm,
- para-hydrogen is $\lambda \approx$ 20 cm
- for a *n-p* capture is $\lambda \approx$ 50cm.

A safe 20-liter Liquid Para-Hydrogen Target



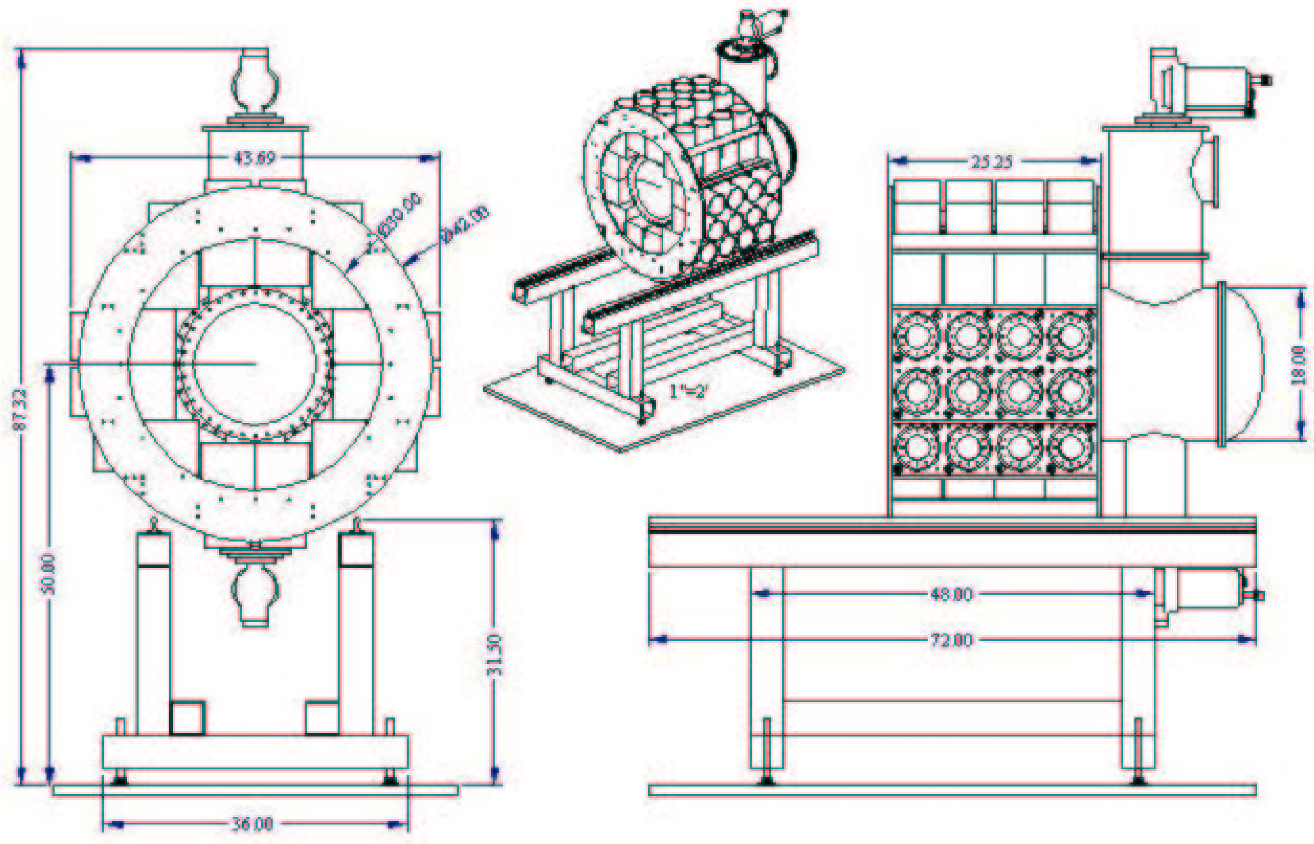
CsI(Tl) Gamma Detector

- Up-down γ – asymmetry will be measured.
- The detector has to be aligned with the B_0 guide field better than 20 mrad.
- CsI(Tl) was selected because of :
  - large number of photoelectrons, measured >1000/MeV γ-ray
  - interaction length of a 2.2-MeV γ-ray in CsI is about 5 cm $\rightarrow$ 95% of γ's will be stopped in 15 cm.
- The gamma detector has 48 CsI modules - 15 x 15 x 15 cm^3. Total of 0.7 metric ton of CsI(Tl).



48 CsI(Tl) detectors have been received and are under testing.

CsI(Tl) Gamma Detector

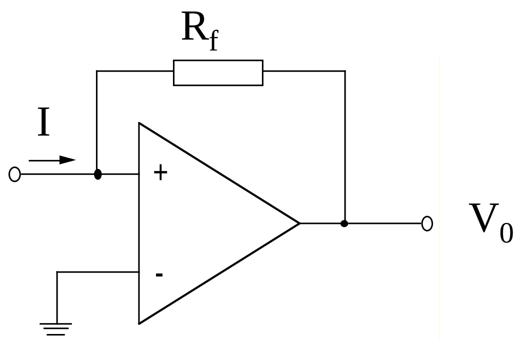


Detector solid angle is ≈ 3π.

Current Mode Detection with Vacuum Photo Diodes

- Rates are about $10^{10}\ \gamma/s \rightarrow$ current mode detection.
- Light from CsI(Tl) is detected by 3” vacuum photodiodes which have S20 photocathodes.
  - vacuum photodiode linearity $< 10^{-4}$ and
  - magnetic field sensitivity $< 10^{-4}$/G and $< 10^{-5}$/G^2
- Vacuum photodiode has a gain of 1 $\rightarrow$ a high-gain low-noise $I \rightarrow V$ preamplifier is required.
- In the current mode detection statistical fluctuations (counting statistics) appear as a shot noise in photodiode current.
- RMS of the shot noise current density is $i_{\text{noise}}/\sqrt{f} = \sqrt{2qI} \approx n_{\text{pe}} e \sqrt{2 \times rate} \approx$ 5 pA/$\sqrt{\text{Hz}}$ per detector.

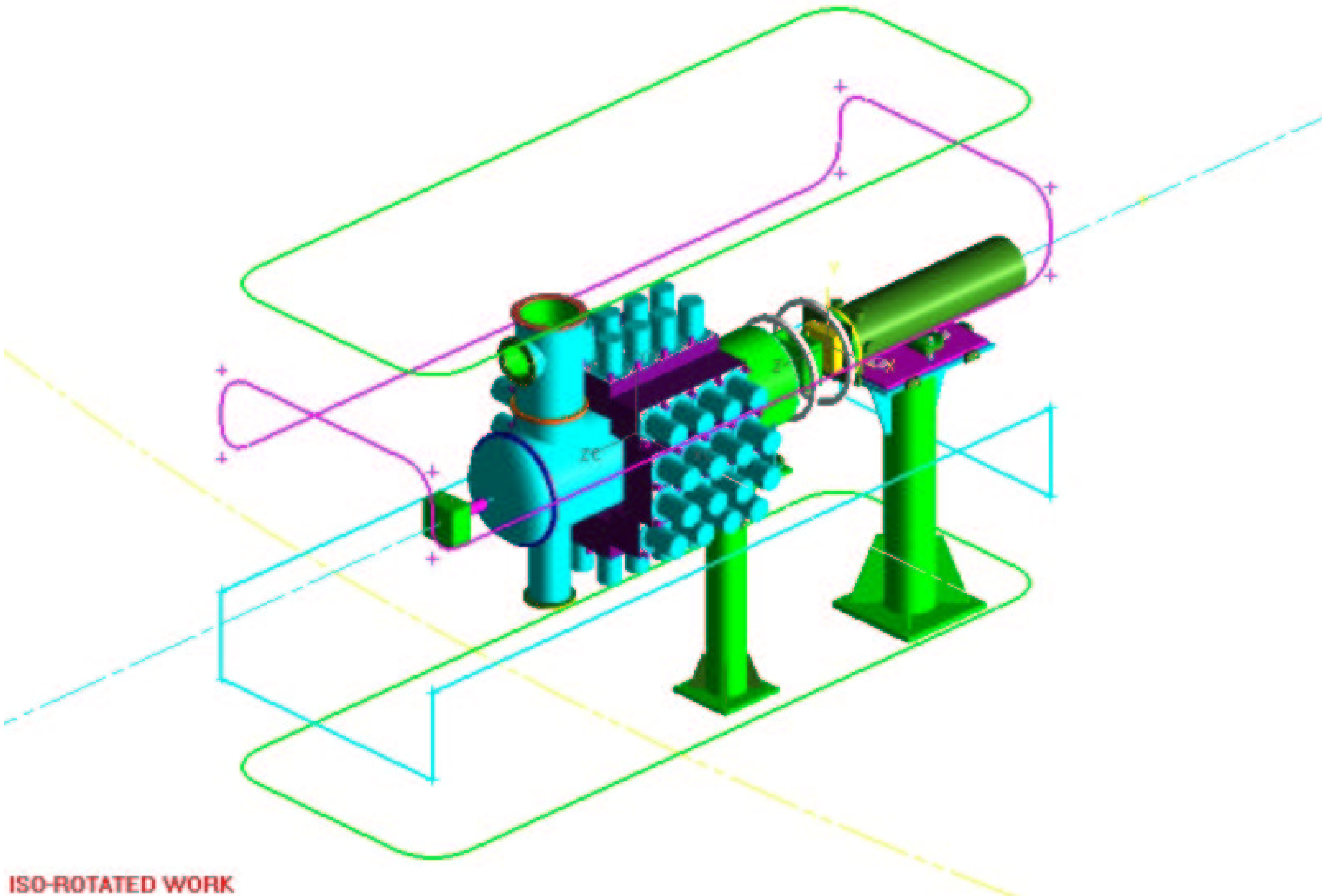
Counting statistics vs electrical noise



- Sources of noise; Johnson noise in R_f, current and voltage noises in the op amp input, and photocathode dark current
- If R_f = 60 MΩ then the total calculated equivalent noise at the input is 19 fA/√Hz dominated by R_f.
- Noise value measured from the circuit is about 20 fA/√Hz.

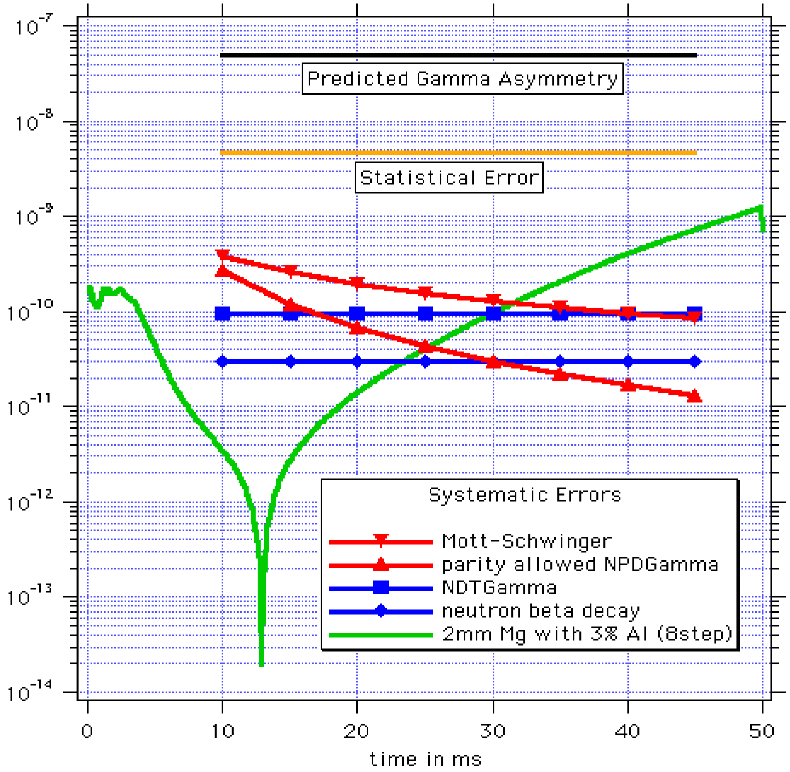
  $\rightarrow$ counting statistics/noise $\approx$ 250.
- Counting statistics rules the run time.
- To measure beam-off false asymmetry to 0.5×10^{-8} beam-off time of a few minutes is needed.

n+p->d+γ Experiment Layout



Systematic Errors

- Physics - correlated with neutron spin:
  - activated materials - emit γs in β-decay
  - Stern-Gerlach steering
  - L-R asymmetry
    - *n* - *p* elastic scattering
    - n - p parity allowed asymmetry
    - Mott-Schwinger scattering
- Instrumental sources
  - electronics, stray magnetic fields, gain stability
- Monitoring:
  - Null test at E_n > 15 meV and at end of each pulse.



Summary

- The $\vec{n}+p \rightarrow d+\gamma$ reaction is the most sensitive way to isolate the neutral current component in the hadronic weak interaction and to determine H_{π}^{1} .
- With pulsed cold neutrons A_γ can be measured with the statistical precision of 5×10^{-8}
  - *In situ* control of systematic errors by *TOF* information.
- The $\vec{n}+p \rightarrow d+\gamma$ experiment will use ^{3}He neutron spin filter, RF spin flipper, and current mode detection.
- Commissioning of the experiment will start in spring 2003.
- An interesting follow-up experiment could be $\vec{n}+d \rightarrow t+\gamma$.